

SIMULATION ANALYSIS OF THE ELECTRODE-ARC INTERACTION IN FREE BURNING ARCS

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ABSTRACT

Electrodes are important constituents of plasma devices determining the properties of arc discharge. The arc-electrode interaction enables the current transfer in the thin near-electrode layer and controls the energy balance and the heating of the electrodes. In this work, an up-to-date nonequilibrium model, aimed at the unified description of the arc from the one electrode to the other, is used to analyse the arc-electrode interaction in a free-burning argon arc at atmospheric pressure. The space-charge sheaths adjacent to the electrodes are treated consistently with the bulk plasma in order to obtain the sheath voltage drops. The heat fluxes toward the electrodes, and the temperatures of heavy particles and electrons, are presented for arc currents of 100-200 A.

1. INTRODUCTION

In spite of a tremendous amount of modelling work considering the electrode-arc interaction (see e.g. the review paper [1] and the references therein), a universally accepted approach is still absent. In many models, the assumption of local thermodynamic equilibrium in the arc column is applied or alternatively, a two-temperature description of the arc plasma is used. Then, the arc model is coupled (or not) to a model of the cathode including (or not) the near-cathode plasma layer. The near-anode region is studied in a series of works ([2, 3], the references therein). Experimental data and theoretical models led to the understanding that the near-anode voltage drop can be both positive and negative and it is smaller than the near-cathode voltage drop. The energy fluxes to the cathode and the anode are substantially different. It has been recognized that self-consistent models of the arc and the electrodes could give the required realistic predictions over a wide range of arc currents provided that they account for nonequilibrium

effects in the near-electrode regions. In a recent work [4], a nonequilibrium model of the arc plasma coupled with a model of the near-cathode sheath has been developed. An important feature of this approach is the treatment of the arc plasma in terms of multi-species (electrons, singly charged ions and atoms) and individual temperatures of electrons and heavy species. Therefore, the model enables the joint treatment of the bulk plasma and the pre-sheath. The space-charge sheath adjacent to the cathode is considered kinetically in the frame of a zero-dimensional model due to its small size in direction perpendicular to the electrode surface. Now, the model has been extended to couple the near-anode space-charged sheath in a way similar to that for the cathode. Simulations are performed for an arc geometry investigated experimentally in [5], so that the calculated arc voltage has been compared with reliable experimental data.

2. DESCRIPTION OF THE MODEL

The model of the argon bulk plasma used in the present investigation is similar to the previously developed one [4] and is only briefly considered. However, the near-electrode regions are described in more detail.

The arc plasma is assumed to be quasineutral. There are separate energy equations for electrons and heavy particles in a way that the electrons are characterized by a Maxwellian energy distribution function with a temperature T_e and the heavy species (atoms and ions) are assumed to have a common temperature T ($T_e \neq T$). The equation of continuity of electric current is combined with Ohm's law and Ampère's law for the self-induced magnetic field to obtain terms appearing in the equation of conservation of momentum (Lorentz force) and energy (Joule heating). Equations of species' conservation account for diffusion and convection processes and chemical reactions. The model of the argon arc plasma can be considered with different levels

of reaction complexity [6]. In order to provide investigations in a wide range of electric current values at reasonable computational costs, the model with simplest reaction scheme and a two-level representation of the atomic argon energy structure is applied here. Hence, two heavy species, atoms and singly charged ions, are considered. The heat conduction equation and the equation of current continuity are solved in the electrode solids.

The nonequilibrium model of the bulk plasma includes the region of quasi-neutral plasma (also called pre-sheath or ionization layer) adjacent to the space-charge sheath. The space-charged sheath adjacent to the cathode is assumed to be collisionless for the ions with Boltzmann-distributed electrons on the interface. The temperature of heavy particles approaches the surface temperature of the electrode. The electric potential has a jump due to the voltage drop in the space-charge sheath. Since the small thickness of the sheath (in the order of the Debye length) it is treated as zero-dimensional interface between the bulk plasma and the electrodes. The current density and the power balance are considered on the edge between the bulk plasma and the electrode sheaths as an enhancement of the ideas proposed in [1,2]. The in- and out-going energy fluxes and the generated and dissipated power in the space-charged sheath are accounted for.

cathode sheath: $j = j_i + j_{em} - j_p$,

$$\begin{aligned} & j_i U_s^c + (j_{em} - j_p)(U_s^c - \Delta\Phi^c) \\ & - \frac{j_i}{e}(2k_B T_{i,s} + \frac{1}{2}k_B T_{e,s} + eU_s^c) - j_i U_i \\ & - \frac{j}{e}3.2k_B T_{e,s} + \frac{j_i}{e}2k_B T_c + \frac{j_{em}}{e}2k_B T_c \\ & - \frac{j_p}{e}2k_B T_{e,s} = 0 \end{aligned} \quad (1)$$

anode sheath: $j = -j_i - j_{em} + j_p$,

$$\begin{aligned} & j_i U_s^a + (j_{em} - j_p)U_s^a \\ & - \frac{j_i}{e}(2k_B T_{i,s} + \frac{1}{2}k_B T_{e,s} + eU_s^a) - j_i U_i \\ & + \frac{j}{e}3.2k_B T_{e,s} + \frac{j_i}{e}2k_B T_a + \frac{j_{em}}{e}2k_B T_a \\ & - \frac{j_p}{e}2k_B T_{e,s} = 0 \end{aligned} \quad (2)$$

The total current density, j , comprises the ion component $j_i = en_{i,s} \sqrt{k_B(T_{i,s} + T_{e,s})/m_i}$, the current density of emitted electrons $j_{em} = A_R T_{c,a}^2 \exp(-e(\Phi^{c,a} - \Delta\Phi^c)/k_B T_{c,a})$, and the contribution of the bulk plasma electrons

$$j_p = \frac{en_{e,s}}{4} \sqrt{8k_B T_{e,s} / \pi m_e} \exp(-eU_s^{c,a} / k_B T_{e,s}),$$

expressed by means of the plasma parameters at the sheath edge electron and ion density ($n_{e,s}$ and $n_{i,s}$), the electron and ion temperatures ($T_{e,s}$ and $T_{i,s}$), the work functions (Φ and Φ^a), the surface temperatures (T_c and T_a) of the cathode and the anode, and the voltage drops (U_s^c and U_s^a) in the cathode and the anode sheath, respectively. The ionization potential of the working gas is denoted by U_i , the Schottky correction of the cathode material is $\Delta\Phi$ (notice that the latter is not considered for the anode material), A_R denotes the Richardson constant, k_B – the Boltzmann constant, m_i – the mass of the bulk ion, m_e – the mass of the electron, and e – the elementary charge. The terms in Eqs. (1) and (2) describe the following contributions. The first and second terms on the left hand side express the electrical power in the sheath, the third term – the kinetic energy of the ions, the fourth – the energy loss due to ionization in the pre-sheath, the fifth – the enthalpy flow with a contribution of thermal diffusion, the sixth – the energy of neutral atoms produced by neutralization of ions at the electrode, the seventh – the energy of electrons emitted from the electrode, the eighth – the kinetic energy of the plasma electrons.

Eqs. (1) and (2) clearly show a similarity in the description of the near-cathode and the near-anode regions. A rearrangement of the terms leads to the following common form

$$j_{em} \cdot a = j_p \cdot b + j_i \cdot c \quad (3)$$

with $a = U_s^{c,a} - \Delta\Phi^c - (3.2T_{e,s} - 2T_{c,a})k_B/e$, $b = U_s^{c,a} - \Delta\Phi^c - (3.2 - 2)T_{e,s}k_B/e$, and $c = U_i + (2T_{i,s} + 0.5T_{e,s})k_B/e + (3.2T_{e,s} - 2T_{c,a})k_B/e$. The solution of Eq. (3) with the plasma parameters obtained on the edge of the nonequilibrium plasma bulk yields the corresponding sheath voltage drop. Then, the additional heat fluxes to the electrodes can be found. They are written as follows

$$q^{c,a} = q_i^{c,a} + q_p^{c,a} - q_{em}^{c,a} - q_{rad}^{c,a}, \quad (4)$$

where the subscripts indicate the origin of the flux (ions, plasma electrons, emitted electrons, radiation), and the superscript – the cathode or the anode. The last term $q_{rad}^{c,a} = \varepsilon_{c,a} \sigma_{SB} T_{c,a}^4$ represents the black-body radiation from the electrode surface with $\varepsilon_{c,a}$ being the emissivity of the electrode, and σ_{SB} – the Stefan-Boltzmann constant. With the notations introduced above, the fluxes can be written as

$$\begin{aligned}
q^{c,a} = & \frac{j_i}{e} \left(2k_B T_{i,s} + \frac{1}{2} k_B T_{e,s} + e(U_s^{c,a} - \Delta\Phi^c) \right) + \\
& + \frac{j_p}{e} (2k_B T_{e,s} + e(\Phi^{c,a} - \Delta\Phi^c)) \\
& - \frac{j_{em}}{e} (2k_B T_{c,a} + e(\Phi^{c,a} - \Delta\Phi^c)) - \varepsilon_{c,a} \sigma_{SB} T_{c,a}^4
\end{aligned} \quad (5)$$

3. RESULTS AND DISCUSSION

The results of the model reported in this work are obtained for a 10 mm long DC arc in atmospheric pressure argon. The tungsten cathode is a cylindrical rod with a diameter of 2 mm and a hemispherical tip. The anode is made of copper and it is water-cooled. The calculations are performed for arc currents from 100 up to 200 A. In order to reproduce the experimental conditions in [5] where the arc is burning in a closed chamber, a gas inflow is not supplied.

The distributions of the heavy particles and electron temperatures in the control volumes adjacent to the electrodes obtained with the solution of the bulk plasma are presented in Figure 1. It is clearly shown that in the near-electrode regions the electron temperature remains well above the temperature of heavy particles, i.e. the plasma state there deviates from thermal equilibrium. The electron temperatures near the arc attachment at the cathode reach values above 12000 K whereas the values corresponding to the attachment at the anode are below 10000 K. Similarly, the temperatures of heavy particles near the cathode tip are higher than those near the anode surface. These temperatures are used in the solution of the sheath balances (Eq. (3)).

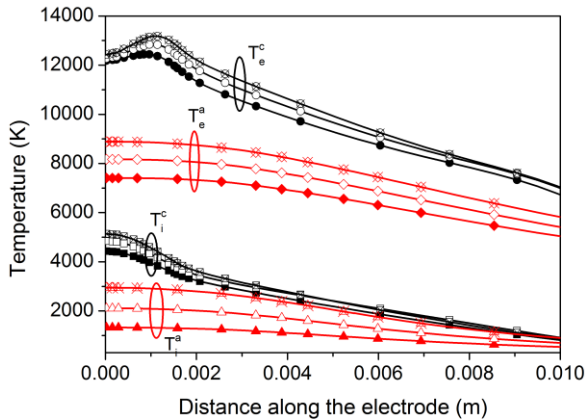


Fig. 1 Temperatures of heavy particles and electrons near the cathode (c) and the anode (a) surface for arc currents of 100 A (solid), 150 A (open), and 200 A (crossed symbols).

Figure 2 shows the calculated voltage on the arc column (U_{ac}), the cathode and the anode sheath

drop (U_s^c , U_s^a), the voltage over the cathode body (U_{cath}), and the total of all (U_{arc}) in comparison with the experimental values reported in [5]. The calculated arc voltage agrees well with the measured values. At arc current of 100 A, the voltage drop in the cathode sheath exceeds the voltage in the arc column nearly by a factor of two. Hence, the cathode sheath provides roughly two thirds of the total voltage. With increasing arc currents, the contribution of the arc column increases whereas that of the cathode sheath decreases. At arc current of 200 A, the contributions of the cathode sheath and the arc column are close to each other whereby the contribution of the cathode sheath is slightly higher. The voltage over the cathode body is in the region 0.15 – 0.3 V. The anode sheath drop is negative and its absolute value increases for the arc currents under consideration from about 0.4 V to about 0.5 V. Therefore, the two main contributions to the arc voltage are the cathode sheath drop and the arc column voltage. Since the cathode sheath drop is in the entire current region the largest component, the physical model of the arc can only be justified provide that the cathode sheath is included.

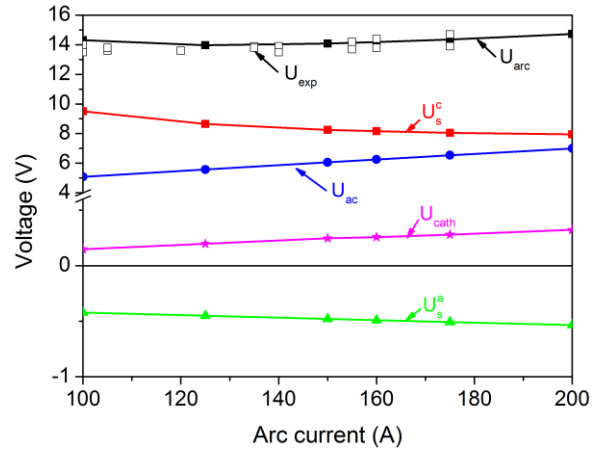


Fig. 2 The arc voltage and its components in comparison with experimental data for various arc currents.

The components of the heat fluxes from the space-charged sheath to the cathode and the anode are presented in Figure 3 along the electrode surface (measured from the arc axis) for arc currents of 100, 150, and 200 A. The solution on the cathode side shows that the main contributions are those of the ions and emitted electrons. Thereby, their absolute values are close to each other in the region of the arc attachment to the cathode body. The ion contribution is slightly larger. Since these fluxes are of opposite signs, the resulting of both becomes lower but it still exceeds the

components due to black-body radiation in the region of the arc attachment. The component due to the plasma electrons is the lowest one even for the arc current value of 200 A. The situation on the anode surface is substantially different. Here, the heat flux due to the plasma electrons exceeds all others by at least one order of magnitude. The cooling of the anode body due to electron emission is of minor importance, being in the range of the radiation cooling only for the highest arc current value.

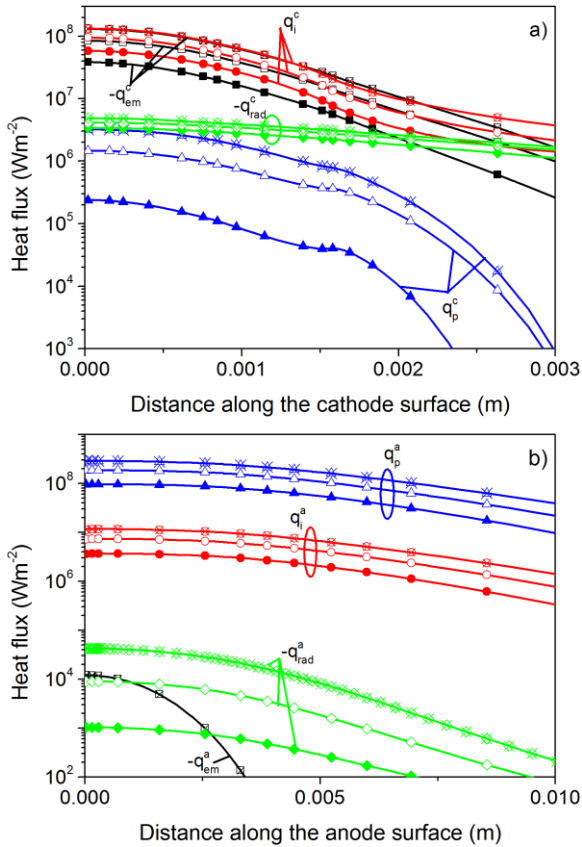


Fig. 3 Heat fluxes along the cathode(a) and the anode (b) surface. Notations with respect to the arc current as in Fig1.

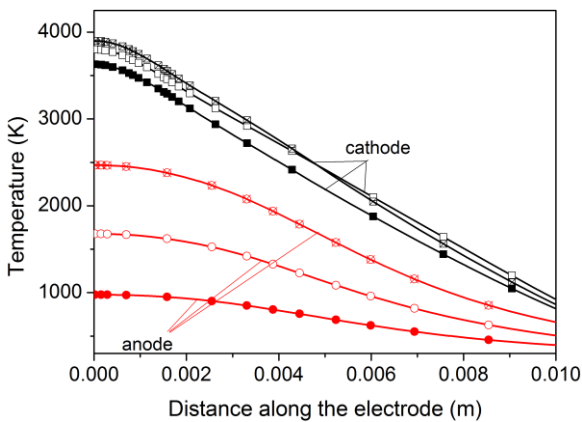


Fig. 4 Temperatures on the cathode and the anode surface. Notations with respect to the arc current as in Fig1.

The temperatures on the surfaces of the electrode bodies are shown in Figure 4. In the centre of the cathode tip, temperatures between 3500 and 3900 K are predicted. Moving in direction to the cathode base, the temperature decreases to 300 K. On the anode surface, the arc attachment area is wider and the maximum temperatures are between 1000 and 2500 K. Notice that the process of material melting is not considered in the present investigation which can lead to temperatures higher than the melting point of tungsten and copper.

4. CONCLUSIONS

The nonequilibrium model of the arc plasma is coupled with 0D models of the cathode and the anode sheaths and applied to an atmospheric pressure free-burning arc in argon for currents of 100-200 A. The calculated arc voltage accounting for the arc column and the electrode sheaths is in a very good agreement with published experimental data. Its main part is due to the voltage drop in the cathode sheath. The arc column voltage increases with the arc current but is still less than the cathode sheath drop for 200 A. The voltage drop in the anode sheath is negative and has values of 0.4-0.5 V. Despite the similar description, the cathode and anode sheaths are substantially different with respect to the heat fluxes to the electrode body.

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